

Theoretical Aspects of Inclusive Light-Hadron Production

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Abstract

We summarize the key results of a recent global analysis of inclusive single-charged-hadron production in high-energy colliding-beam experiments. In the framework of the parton model of quantum chromodynamics at next-to-leading order (NLO), fragmentation functions (FFs) for charged pions, charged kaons, and (anti) protons are extracted from experimental data of e^+e^- annihilation at the Z -boson resonance and at centre-of-mass energy $\sqrt{s} = 29$ GeV. This fit also yields a new NLO value for the strong-coupling constant, namely $\alpha_s^{(5)}(M_Z) = 0.1170 \pm 0.0073$. The scaling violations encoded in the FFs through the Altarelli-Parisi evolution equations are tested by confronting e^+e^- -annihilation data from DESY DORIS, DESY PETRA, and CERN LEP2 with NLO predictions based on these FFs. Comparisons of $p\bar{p}$ data from CERN $Spp\bar{p}S$ and the Fermilab Tevatron, γp data from DESY HERA, and $\gamma\gamma$ data from LEP2 with the corresponding NLO predictions allow us to test the universality of the FFs predicted by the factorization theorem.

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1 Introduction

In the framework of the QCD-improved parton model, the inclusive production of single hadrons is described by means of fragmentation functions (FFs), $D_a^h(x, \mu^2)$. The value of $D_a^h(x, \mu^2)$ corresponds to the probability for the parton a produced at short distance $1/\mu$ to form a jet that includes the hadron h carrying the fraction x of the longitudinal momentum of a . Unfortunately, it is not yet possible to calculate the FFs from first principles, in particular for hadrons with masses smaller than or comparable to the asymptotic scale parameter, Λ . However, given their x dependence at some energy scale μ , the evolution with μ may be computed perturbatively in QCD using the timelike Altarelli-Parisi equations [1]. This allows us to test QCD quantitatively within one experiment observing single hadrons at different values of centre-of-mass (CM) energy \sqrt{s} (in the case of e^+e^- annihilation) or transverse momentum p_T (in the case of scattering). Moreover, the factorization theorem guarantees that the $D_a^h(x, \mu^2)$ functions are independent of the

process in which they have been determined, and represent a universal property of h . This enables us to make quantitative predictions for other types of experiments as well.

After the pioneering leading-order (LO) analyses of pion, kaon, and charmed-meson FFs in the late 1970s [2], there had long been no progress on the theoretical side of this field. In the mid 1990s, next-to-leading-order (NLO) FF sets for π^0 , π^\pm , K^\pm , and η mesons were constructed through fits to data of e^+e^- annihilation, mostly generated with Monte Carlo event generators [3]. In 1994/95, the author, in collaboration with Binnewies and Kramer, extracted π^\pm and K^\pm FFs through fits to SLAC-PEP and partially preliminary CERN-LEP1 data and thus determined the strong-coupling constant to be $\alpha_s^{(5)}(M_Z) = 0.118$ (0.122) at NLO (LO) [4] (BKK). However, these analyses suffered from the lack of specific data on the fragmentation of tagged quarks and gluons to π^\pm , K^\pm , and p/\bar{p} hadrons.

During the last five years, the experiments at LEP1 and SLAC SLC have provided us with a wealth of high-precision information on how partons fragment into low-mass charged hadrons, so as to cure this problem. The data partly comes as light-, c -, and b -quark-enriched samples without [5,6,7] or with identified final-state hadrons (π^\pm , K^\pm , and p/\bar{p}) [8,9,10] or as gluon-tagged three-jet samples without hadron identification [11,12,13]. Motivated by this new situation, the author, together with Kramer and Pötter, recently updated, refined, and extended the BKK [4] analysis by generating new LO and NLO sets of π^\pm , K^\pm , and p/\bar{p} FFs [14].¹ By also including in our fits π^\pm , K^\pm , and p/\bar{p} data (without flavour separation) from PEP [15], with CM energy $\sqrt{s} = 29$ GeV, we obtained a handle on the scaling violations in the FFs, which enabled us to determine the strong-coupling constant. We found $\alpha_s^{(5)}(M_Z) = 0.1181 \pm 0.0085$ at LO and $\alpha_s^{(5)}(M_Z) = 0.1170 \pm 0.0073$ at NLO [16]. These results are in perfect agreement with what the Particle Data Group currently quotes as the world average, $\alpha_s^{(5)}(M_Z) = 0.1181 \pm 0.002$ [17]. Our strategy was to only include in our fits LEP1 and SLC data with both flavour separation and hadron identification [8,9,10], gluon-tagged three-jet samples with a fixed gluon-jet energy [11,12], and the π^\pm , K^\pm , and p/\bar{p} data sets from the pre-LEP1/SLC era with the highest statistics and the finest binning in x [15]. Other data served us for cross checks. In particular, we probed the scaling violations in the FFs through comparisons with π^\pm , K^\pm , and p/\bar{p} data from DESY DORIS and DESY PETRA, with CM energies between 5.4 and 34 GeV [18]. Furthermore, we tested the gluon FF, which enters the unpolarized cross section only at NLO, by comparing our predictions for the longitudinal cross section, where it already enters at LO, with available data [5,19]. Finally, we directly compared our gluon FF with the one recently measured by DELPHI in three-jet production with gluon identification as a function of x at various energy scales μ [13]. All these comparisons led to rather encouraging results. We also verified that our FFs satisfy reasonably well the momentum sum rules, which we did not impose as constraints on our fits.

Very recently, we extended our previous tests of scaling violations [14] to higher energy scales by confronting new data on inclusive charged-hadron production in e^+e^- annihila-

¹A FORTRAN subroutine which returns the values of the $D_a^h(x, \mu^2)$ functions for given values of x and μ^2 may be downloaded from the URL <http://www.desy.de/~poetter/kkp.html> or obtained upon request from the authors.

tion from LEP2 [20], with \sqrt{s} ranging from 133 GeV up to 189 GeV, with NLO predictions based on our FFs [21]. Furthermore, we quantitatively checked the universality of our FFs by making comparisons with essentially all available high-statistics data on inclusive charged-hadron production in colliding-beam experiments [21]. This includes $p\bar{p}$ data from the UA1 and UA2 Collaborations [22] at CERN $S\bar{p}\bar{p}S$ and from the CDF Collaboration [23] at the Fermilab Tevatron, γp data from the H1 and ZEUS Collaborations [24] at DESY HERA, and $\gamma\gamma$ data from the OPAL Collaboration [25] at LEP2.

In 2000, alternative sets of NLO FFs for π^\pm , K^\pm [26], and charged hadrons [26,27] have become available. They are based on different collections of experimental data and on additional theoretical assumptions. In Ref. [26], power laws were assumed to implement a hierarchy among the valence- and sea-quark FFs. In Ref. [27], the renormalization and factorization scales were identified and adjusted according to the principle of minimal sensitivity [28]. In order to estimate the present systematic uncertainties in the FFs, we compare NLO predictions for inclusive charged-hadron production consistently evaluated with the three new-generation FF sets [14,26,27].

In this contribution, we summarize the key results obtained in Refs. [14,16,21]. In Section 2, we present some details of our global fits and assess the quality of the resulting FFs. In Section 3, we discuss the determination of $\alpha_s^{(5)}(M_Z)$ from the scaling violations in the FFs and compare our NLO result with those of different determinations. In Section 4, we present comparisons of our NLO predictions for inclusive charged-hadron production with e^+e^- data from LEP2 [20], $p\bar{p}$ data from $S\bar{p}\bar{p}S$ [22] and the Tevatron [23], γp data from HERA [24], and $\gamma\gamma$ data from LEP2 [25]. Our conclusions are summarized in Section 5.

2 Determination of the FFs

The NLO formalism for extracting FFs from measurements of the cross section $d\sigma/dx$ of inclusive hadron production in e^+e^- annihilation was comprehensively described in Ref. [4]. We work in the $\overline{\text{MS}}$ renormalization and factorization scheme and choose the renormalization scale μ and the factorization scale M_f to be $\mu = M_f = \xi\sqrt{s}$, except for gluon-tagged three-jet events, where we put $\mu = M_f = 2\xi E_{\text{jet}}$, with E_{jet} being the gluon jet energy in the CM frame. Here, the dimensionless parameter ξ is introduced to determine the theoretical uncertainty in $\alpha_s^{(5)}(M_Z)$ from scale variations. As usual, we allow for variations between $\xi = 1/2$ and 2 around the default value 1. For the actual fitting procedure, we use x bins in the interval $0.1 \leq x \leq 1$ and integrate the theoretical functions over the bin widths as is done in the experimental analyses. The restriction at small x is introduced to exclude events in the region where mass effects and nonperturbative intrinsic-transverse-momentum effects are important and the underlying formalism is insufficient. On the other hand, our analysis should be rather insensitive to nonperturbative effects at x values close to 1, since the experimental errors are very large there. We parameterize the x dependence of the FFs at the starting scale μ_0 as $D_a^h(x, \mu_0^2) = Nx^\alpha(1-x)^\beta$. We treat N , α , and β as independent fit parameters. In addition, we take the asymptotic scale parameter $\Lambda_{\overline{\text{MS}}}^{(5)}$, appropriate for five quark flavors, as a free parameter.

Table 1: CM energies, types of data, and χ^2_{DF} values obtained at LO and NLO for the various data samples.

\sqrt{s} [GeV]	Data type	χ^2_{DF} in NLO (LO)	
29.0	σ^π (all)	0.64 (0.71) [15]	
	σ^K (all)	1.86 (1.40) [15]	
	σ^p (all)	0.79 (0.70) [15]	
91.2	σ^h (all)	1.28 (1.40) [9]	1.32 (1.44) [10]
	σ^h (uds)	0.20 (0.20) [9]	
	σ^h (b)	0.43 (0.41) [9]	
	σ^π (all)	1.28 (1.65) [8]	
		0.58 (0.60) [9]	3.09 (3.13) [10]
	σ^π (uds)	0.72 (0.73) [9]	1.87 (2.17) [10]
	σ^π (c)		1.36 (1.16) [10]
	σ^π (b)	0.57 (0.58) [9]	1.00 (0.99) [10]
	σ^K (all)	0.30 (0.32) [8]	
		0.86 (0.79) [9]	0.44 (0.45) [10]
	σ^K (uds)	0.53 (0.60) [9]	0.65 (0.64) [10]
	σ^K (c)		2.11 (1.90) [10]
	σ^K (b)	0.14 (0.14) [9]	1.21 (1.23) [10]
	σ^p (all)	0.93 (0.80) [8]	
		0.09 (0.06) [9]	0.79 (0.70) [10]
	σ^p (uds)	0.11 (0.14) [9]	1.29 (1.28) [10]
	σ^p (c)		0.92 (0.89) [10]
	σ^p (b)	0.56 (0.62) [9]	0.97 (0.89) [10]
E_{jet} [GeV]			
26.2	D^h_g	1.19 (1.18) [11]	
40.1	D^h_g	1.03 (0.90) [12]	

Thus, we have a total of 46 independent fit parameters. The quality of the fit is measured in terms of the χ^2 value per degree of freedom, χ^2_{DF} , for all selected data points. Using a multidimensional minimization algorithm [29], we search this 46-dimensional parameter space for the point at which the deviation of the theoretical prediction from the data becomes minimal.

The χ^2_{DF} values achieved for the various data sets used in our LO and NLO fits may be seen from Table 1. Most of the χ^2_{DF} values lie around unity or below, indicating that the fitted FFs describe all data sets within their respective errors. In general, the χ^2_{DF} values come out slightly in favor for the DELPHI [9] data. The overall goodness of the NLO (LO) fit is given by $\chi^2_{\text{DF}} = 0.98$ (0.97). The goodness of our fit may also be judged from Figs. 1(a) and 1(b), where our LO and NLO fit results are compared with the ALEPH [8,11], DELPHI [9], OPAL [12], and SLD [10] data. In Fig. 1(a), we study the differential cross section $(1/\sigma_{\text{tot}})d\sigma^h/dx$ for π^\pm , K^\pm , p/\bar{p} , and unidentified charged hadrons at $\sqrt{s} = 91.2$ GeV, normalized to the total hadronic cross section σ_{tot} , as a

function of the scaled momentum $x = 2p_h/\sqrt{s}$. As in Refs. [9,10], we assume that the sum of the π^\pm , K^\pm , and p/\bar{p} data exhaust the full charged-hadron data. We observe that, in all cases, the various data are mutually consistent with each other and are nicely described by the LO and NLO fits, which is also reflected in the relatively small χ^2_{DF} values given in Table 1. The LO and NLO fits are almost indistinguishable in those regions of x , where the data have small errors. At large x , where the statistical errors are large, the LO and NLO results sometimes moderately deviate from each other. In Fig. 1(b), we compare the ALEPH [11] and OPAL [12] measurements of the gluon FF in gluon-tagged charged-hadron production, with $E_{\text{jet}} = 26.2$ and 40.1 GeV, respectively, with our LO and NLO fit results. The data are nicely fitted, with χ^2_{DF} values of order unity, as may be seen from Table 1. By the same token, this implies that these data sets [11,12] are mutually consistent.

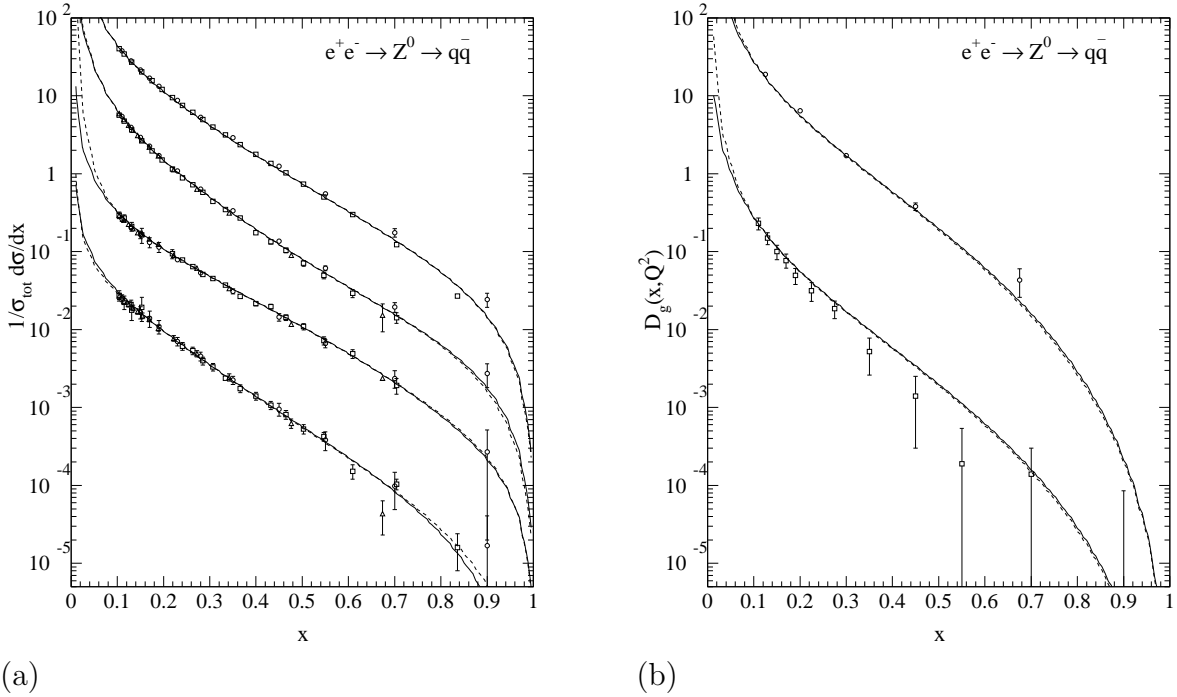


Figure 1: (a) Comparison of data on inclusive charged-hadron production at $\sqrt{s} = 91.2$ GeV from ALEPH [8] (triangles), DELPHI [9] (circles), and SLD [10] (squares) with our LO (dashed lines) and NLO (solid lines) fit results. The upmost, second, third, and lowest curves refer to charged hadrons, π^\pm , K^\pm , and p/\bar{p} , respectively. (b) Comparison of three-jet data on the gluon FF from ALEPH [11] with $E_{\text{jet}} = 26.2$ GeV (upper curves) and from OPAL [12] with $E_{\text{jet}} = 40.1$ GeV (lower curves) with our LO (dashed lines) and NLO (solid lines) fit results.

3 Determination of $\alpha_s^{(5)}(M_Z)$

Since we included in our fits high-quality data from two very different energies, namely 29 and 91.2 GeV, we are sensitive to the running of $\alpha_s(\mu)$ and are, therefore, able to extract values of $\Lambda_{\overline{\text{MS}}}^{(5)}$. We obtain $\Lambda_{\overline{\text{MS}}}^{(5)} = 88^{+34}_{-31} {}^{+3}_{-23}$ MeV at LO and $\Lambda_{\overline{\text{MS}}}^{(5)} = 213^{+75}_{-73} {}^{+22}_{-29}$ MeV at NLO, where the first errors are experimental and the second ones are theoretical. The experimental errors are determined by varying $\Lambda_{\overline{\text{MS}}}^{(5)}$ in such a way that the total χ^2_{DF} value is increased by one unit if all the other fit parameters are kept fixed, while the theoretical errors are obtained by repeating the LO and NLO fits for the scale choices $\xi = 1/2$ and 2. From the LO and NLO formulas for $\alpha_s^{(n_f)}(\mu)$, we thus obtain

$$\begin{aligned}\alpha_s^{(5)}(M_Z) &= 0.1181^{+0.0058}_{-0.0069} {}^{+0.0006}_{-0.0049} & (\text{LO}), \\ \alpha_s^{(5)}(M_Z) &= 0.1170^{+0.0055}_{-0.0069} {}^{+0.0017}_{-0.0025} & (\text{NLO}),\end{aligned}\tag{1}$$

respectively. As expected, the theoretical error is significantly reduced as we pass from LO to NLO. Adding the maximum experimental and theoretical deviations from the central values in quadrature, we find $\Lambda_{\overline{\text{MS}}}^{(5)} = (88 \pm 41)$ MeV and $\alpha_s^{(5)}(M_Z) = 0.1181 \pm 0.0085$ at LO and $\Lambda_{\overline{\text{MS}}}^{(5)} = (213 \pm 79)$ MeV and $\alpha_s^{(5)}(M_Z) = 0.1170 \pm 0.0073$ at NLO. We observe that our LO and NLO values of $\alpha_s^{(5)}(M_Z)$ are quite consistent with each other, which indicates that our analysis is perturbatively stable. The fact that the respective values of $\Lambda_{\overline{\text{MS}}}^{(5)}$ significantly differ is a well-known feature of the $\overline{\text{MS}}$ definition of $\alpha_s^{(n_f)}(\mu)$ [30].

Our values of $\Lambda_{\overline{\text{MS}}}^{(5)}$ and $\alpha_s^{(5)}(M_Z)$ perfectly agree with those presently quoted by the Particle Data Group (PDG) [17] as world averages, $\Lambda_{\overline{\text{MS}}}^{(5)} = 208^{+25}_{-23}$ MeV and $\alpha_s^{(5)}(M_Z) = 0.1181 \pm 0.002$, respectively. Notice that, in contrast to our LO and NLO analyses, the PDG evaluates $\Lambda_{\overline{\text{MS}}}^{(5)}$ from $\alpha_s^{(5)}(M_Z)$ using the three-loop relationship [30]. The PDG combines twelve different kinds of $\alpha_s^{(5)}(M_Z)$ measurements, including one from the scaling violations in the FFs [31], by minimizing the total χ^2 value and thus obtains $\alpha_s^{(5)}(M_Z) = 0.1181 \pm 0.0014$ with $\chi^2 = 3.8$. The world average cited above is then estimated from the outcome by allowing for correlations between certain systematic errors. It is interesting to investigate how the world average of $\alpha_s^{(5)}(M_Z)$ is affected by our analysis. If we replace the value $\alpha_s^{(5)}(M_Z) = 0.125 \pm 0.005 \pm 0.008$ resulting from previous FF analyses [31], which enters the PDG average, with our new NLO value, then we obtain $\alpha_s^{(5)}(M_Z) = 0.1180 \pm 0.0014$ with $\chi^2 = 3.22$, *i.e.*, the face value of the world average essentially goes unchanged, while the overall agreement is appreciably improved. This is also evident from the comparison of Fig. 2, which summarizes our updated world average, with the corresponding Fig. 9.1 in Ref. [17]. We observe that the central value of our new NLO result for $\alpha_s^{(5)}(M_Z)$ falls into the shaded band, which indicates the error of the world average, while in Fig. 9.1 of Ref. [17] the corresponding central value [31] exceeds the world average by 3.5 standard deviations of the latter, which is more than for all other eleven processes. Furthermore, our new NLO result has a somewhat smaller error (0.0073) than the corresponding result [31] used by the PDG (0.009). This is due to a marked

decrease in the theoretical error, which may be attributed to a different choice of input data, especially at low CM energies. If we take the point of view that our new NLO value of $\alpha_s^{(5)}(M_Z)$ should rather be combined with the result from the previous FF analyses [31] before taking the world average, then the latter turns out to be $\alpha_s^{(5)}(M_Z) = 0.1181 \pm 0.0014$ with $\chi^2 = 3.34$.

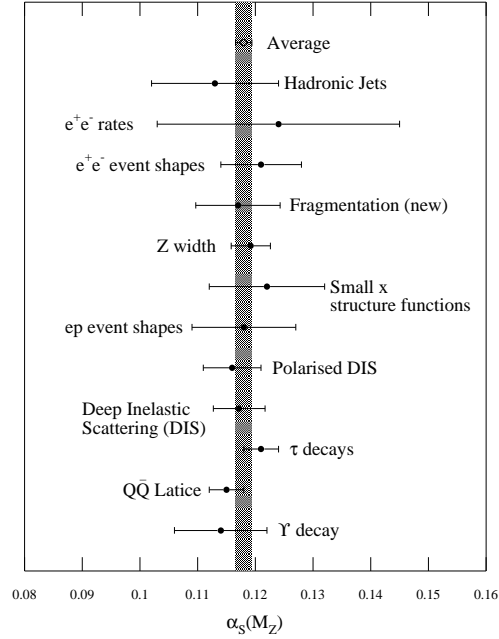


Figure 2: Summary of the values of $\alpha_s^{(5)}(M_Z)$ from various processes. The errors shown represent the total errors including theoretical uncertainties.

4 Global Analysis of Collider Data

We now review recent tests of the scaling violations and the universality of our FFs [21]. On the one hand, we confronted new data on inclusive charged-hadron production from LEP2 [20], with CM energies ranging from 133 GeV to 189 GeV, with our NLO predictions. On the other hand, we performed a global NLO analysis of essentially all high-statistics data on inclusive charged-hadron production in colliding-beam experiments, including $p\bar{p}$ scattering at $Spp\bar{S}$ [22] and the Tevatron [23], γp scattering at HERA [24], and $\gamma\gamma$ scattering at LEP2 [25]. In the cases of hadroproduction and photoproduction, we set $\mu = M_f = \xi p_T$. As for the parton density functions (PDFs) of the proton, we employ set CTEQ5M provided by the CTEQ Collaboration [32], with $\Lambda_{\overline{\text{MS}}}^{(5)} = 226$ MeV. As for the

photon PDFs, we use the set by Aurenche, Fontannaz, and Guillet (AFG) [33]. In the following, we always consider the sum of positively and negatively charged hadrons.

In all cases, we found reasonable agreement between the experimental data and our NLO predictions as for both normalization and shape, as may be seen from Fig. 3. The majority of the data sets are best described with the central scale choice $\xi = 1$. Exceptions include the UA1 data sets with $\sqrt{s} = 200$ and 630 GeV and the UA2 data set with $1 < |y| < 1.8$, which prefer $\xi = 1/2$, as well as the ZEUS data, which favours $\xi = 2$. However, if we estimate the theoretical uncertainty due to unknown corrections beyond NLO by varying ξ between 1/2 and 2, as is usually done, then it is justified to state that all the considered data sets agree with our NLO predictions within their errors. We hence conclude that our global analysis of inclusive charged-hadron production provides evidence that both the predicted scaling violations and the universality of the FFs are realized in nature.

5 Conclusions

Owing to the high-statistics experimental information on how partons fragment into low-mass charged hadrons provided by the LEP1 and SLC experiments, the determination of NLO FFs advanced to a level of precision which is comparable to the one familiar from similar analyses for PDFs. In this presentation, we reviewed recent LO and NLO analyses of π^\pm , K^\pm , and p/\bar{p} FFs [14], which also yielded new values for $\alpha_s^{(5)}(M_Z)$ [16]. Although these FFs are genuinely nonperturbative objects, they possess two important properties that follow from perturbative considerations within the QCD-improved parton model and are amenable to experimental tests, namely scaling violations and universality. The scaling violations were tested [14,21] by making comparisons with data of e^+e^- annihilation at CM energies below [18] and above [20] those pertaining to the data that entered the fits. The universality property was checked [21] by performing a global study of high-energy data on hadroproduction in $p\bar{p}$ collisions [22,23] and on photoproduction in $e^\pm p$ [24] and e^+e^- [25] collisions.

As is well known, the gluon FF enters the prediction for the unpolarized cross section of inclusive hadron production in e^+e^- annihilation only at NLO, while at LO it only contributes indirectly via the μ^2 evolution. In order to nevertheless have a handle on it, we included in our fits [14] experimental data on gluon-tagged three-jet events from LEP1 [11,12]. Furthermore, we checked that our predictions for the longitudinal cross section, where it already enters at LO, agree well with available data [5,19]. On the other hand, the gluon FF is known to play a crucial rôle for $p\bar{p}$, γp , and $\gamma\gamma$ scattering at low values of p_T . Thus, the comparisons performed here provide another nontrivial test of the gluon FF.

As we have seen in Fig. 3, the theoretical uncertainty of the NLO predictions due to scale variations significantly decreases as p_T increases. In order to perform more meaningful comparisons, it would, therefore, be desirable if $p\bar{p}$, γp , and $\gamma\gamma$ experiments extended their measurements out to larger values of p_T . Furthermore, in order to render such com-

parisons more specific, it would be useful if these experiments provided us with separate data samples of π^\pm , K^\pm , and p/\bar{p} hadrons.

We also estimated the current systematic uncertainties in the FFs by comparing our NLO predictions for flavour-tagged inclusive charged-hadron production with those obtained from two other up-to-date FF sets [26,27]. Apart from a difference in the b -quark FFs at medium to large values of x , which may be traced to the incompatibility of two underlying b -quark-specific data samples [7,9], all three FF sets [14,26,27] mutually agree within the present experimental errors.

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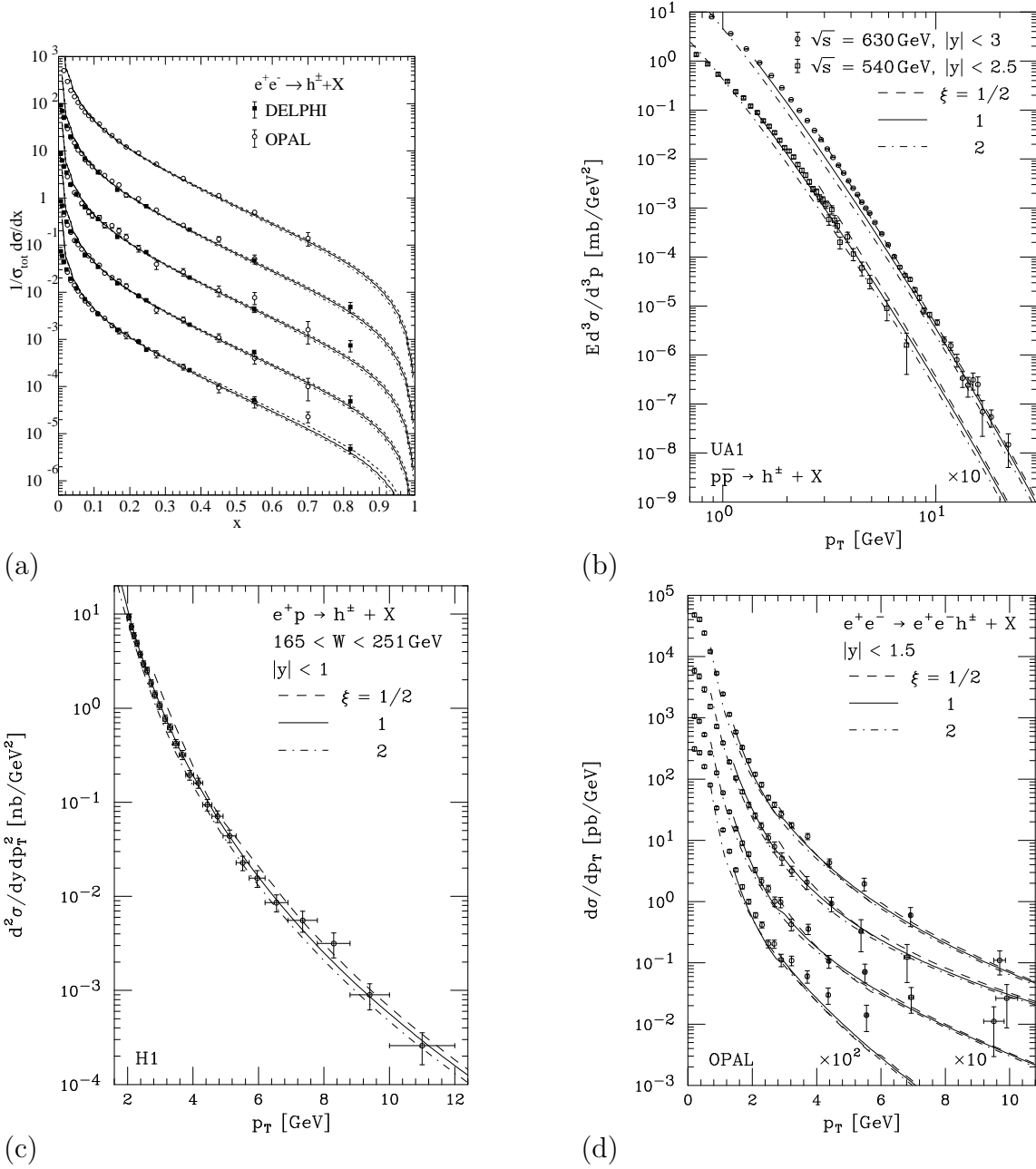


Figure 3: Comparisons of data on inclusive charged-hadron production in (a) e^+e^- annihilation at LEP2 with $\sqrt{s} = 133, 161, 172, 183$, and 189 GeV (from bottom to top in this order), (b) $p\bar{p}$ scattering at $Sp\bar{p}S$, (c) γp scattering at HERA, and (d) $\gamma\gamma$ scattering at LEP2 integrated over $\gamma\gamma$ -invariant-mass intervals $10 < W < 30$ GeV, $30 < W < 55$ GeV, $55 < W < 125$ GeV, and $10 < W < 125$ GeV (from bottom to top in this order) with NLO predictions based on our FFs.